Status report on the EOS validation investigation:
Surface Radiation Budget and Cloud Measurements for NASA's EOS CERES Program

John Augustine and Chuck Long
May 26, 2000

Synopsis of objectives

The objective of this investigation is to use SURFRAD network data, and special research-supporting ancillary measurements and analyses to provide validation data for the three CERES-equipped EOS satellites, TRMM, TERRA and PM. We are presently in middle of the third year of a three-year contract. The goals of third year were:

1) continue with the re-analysis,
2) complete studies of the effects of clouds on the surface radiation budget,
3) submit manuscripts for publication.

While the third year's schedule appears to be limited in research tasks, the accomplishments for year three include the completion of tasks that were delayed from previous years.

Accomplishments

Total Sky Imagers installed

The hemispheric sky imager (HSI) was designed and developed at SRRB (Long and DeLuisi, 1998). Originally, SRRB was to build these devices for the SURFRAD stations, however, it was decided to have it produced commercially. It was believed that this would result in a technically superior, environmentally hardened product with greater longevity. Yankee Environmental Systems, Inc. (YES) designed the commercial version based on the SRRB prototype and now manufactures it as the Total Sky Imager (TSI). This resulted in a one year delay in the deployment of the cloud imagers at SURFRAD stations. Besides one-minute hemispheric sky images, other products provided by the TSI include cloud fraction for all clouds, for opaque clouds, and for thin clouds. Several improvements were introduced by YES, including the ability to keep track of the cloud fraction in the circular area in the middle of the hemispheric sky image (that is blocked by the camera), and the ability to keep track of the clear/cloudy pixels in the area along the horizon at the solar azimuth, and in a circle around the solar position. The latter two areas are usually white in the images owing to camera threshold limitations, regardless of the presence of clouds. Keeping track of the clear/cloudy pixels in these areas is intended to allow a second pass processing to help alleviate the camera's CCD range limitations. They also added a sunshine meter that determines whether the sun, which can't be viewed because of the sun blocking strip, is blocked by cloud.

In 1998 the first TSI was installed at the Penn State SURFRAD station. Since the summer of 1999 TSIs have been installed at all SURFRAD stations except Fort Peck. The installation at Desert Rock occurred in May 1999; Table Mountain's followed in June, and the Goodwin Creek and Bondville TSIs were installed in September. The latter four are quite robust; i. e., the TSI was placed on a metal platform at the top of a post that was set in concrete and guyed for stability (Fig. 1), all wiring was run through conduit, the controlling computers were housed in a safe environment, and bird deterrents were installed. Fort Peck will require special housing for the computer, which will be addressed this year.

The TSI's must be optimized for each site. This is an iterative process that requires setting the camera parameters, watching the cloud definitions for several weeks, and adjusting the operating parameters as necessary. This process must be repeated until the operators are satisfied with the cloud definitions and cloud fractions. These "tuning" exercises been ongoing during the past winter and spring for the latest four installations.

Fig 1: The Total Sky Imager at the Goodwin Creek SURFRAD station. Note the liquid tight conduit and guy wires. The ribbons were a temporary bird deterrent that were eventually replaced with an electronic device that was placed in the looped brackets evident below the square support plate.

TSI data access for EOS investigators

One-minute hemispheric sky images are stored locally on a removable large-capacity jaz disk at the TSI computer. This disk is exchanged with a blank one every two months and returned to SRRB. Hourly images and one-minute cloud fraction files are downloaded daily from each site and checked. An ftp site has been set up for NASA EOS investigators to retrieve the one-hour sky images, processed images, and cloud fraction files. All cloud fraction files and the latest two weeks of hourly images are available. To get these data, ftp to <space.srrb.noaa.gov> and log on as “anonymous,” using your complete email address as the password. To locate the TSI directory tree, change directories to /pub/TSI. There are two subdirectories below that, one for one-minute cloud fraction data, and the other for hemispheric sky images, i. e. /CloudFrac and /Daily. The directory /pub/TSI/CloudFrac contains subdirectories that correspond to each station called BDN-CF, FPK-CF, DRA-CF, GWN-CF, TBL-CF, and PSU-CF. It also has a readme-CF file that explains the structure of the cloud fraction files. Cloud fraction filenames are of the form [sta]yyyymmdd.txt, where [sta] refers to bnd, fpk, gwn, tbl, dra, and psu.

Subdirectory /pub/TSI/Daily contains station subdirectories called BND-Images, DRA-Images, FPK-Images, GWN-Images, PSU-Images, and TMT-Images. These contain the latest two weeks of hourly sky hemispheric images and the corresponding processed (decision) images. Processed images illustrate the TSI interpretations using blue for clear sky, white for opaque cloud, and gray for thin cloud. The hemispheric sky images are in JPEG format and filenames are of the form [sta]yyyymmddhhmmss.jpg. Processed image files have the same file naming convention, but use .png as the extension.

Clear-sky detection, cloud fraction, and Cloud effects data available

The adaptation of the clear-sky detection algorithm (Long and Ackerman, 2000) to SURFRAD data was completed and tested previously. In addition to objectively detecting clear sky periods, this algorithm fits functions to the detected clear sky irradiance values as a function of the cosine of the solar zenith angle. The function thus provides estimates of clear-sky irradiance for all times of day. Comparing the estimated clear-sky irradiance (from the function) to the measured irradiance for the same times yields an objective determination of cloud effect. Coefficients of best-fit equations that were derived for the diurnal cycle of clear-sky irradiance for quasi-clear days are interpolated for intervening cloudy days, thus providing a continuous record of estimated clear-sky irradiance and cloud effect. This algorithm is typically run on SURFRAD data on a monthly basis. Since results can only be produced up through the last quasi-clear day of the record, this is not a real-time product.

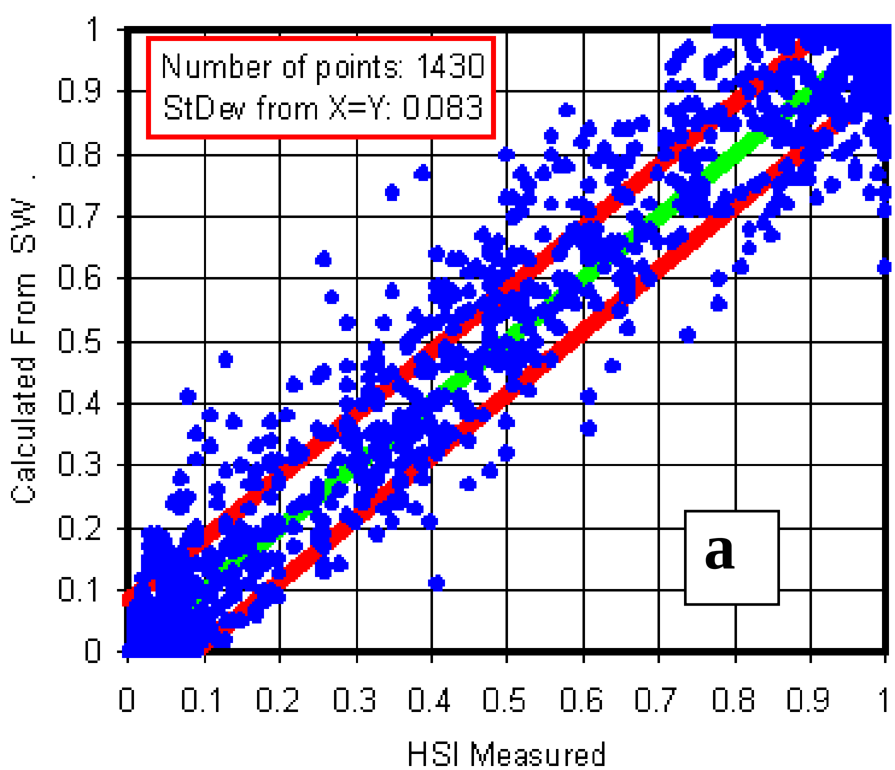
All SURFRAD data through the present have been processed for cloud effect. The clear-sky fit and shortwave forcing data are in files with .c15 and .sfw extensions. The .swf files are at the resolution of the SURFRAD data (three min.). The .c15 files have 15-minute averages of the values in the .swf files, and also contain estimated fractional cloud cover information (discussed in the next section). Presently, these results are available from the beginning of the SURFRAD record through the present at the SRRB anonymous ftp site ftp.srrb.noaa.gov . We plan to update these on a monthly basis. To access these data, log on to the ftp site as an anonymous user, and change directories to /pub/data/NASA_EOS/. Below NASA_EOS are station subdirectories: /bon, /fpk, /gwn, /tbl, /dra, /psu. Under each station directory are two subdirectories, /c15, and /swf. Filenames are of the form yyyymmdd.c15 and yyyymmdd.swf. Readme files (c15_readme.txt and swf_readme.txt) that explain the format of these files are included at the station level of the directory structure.

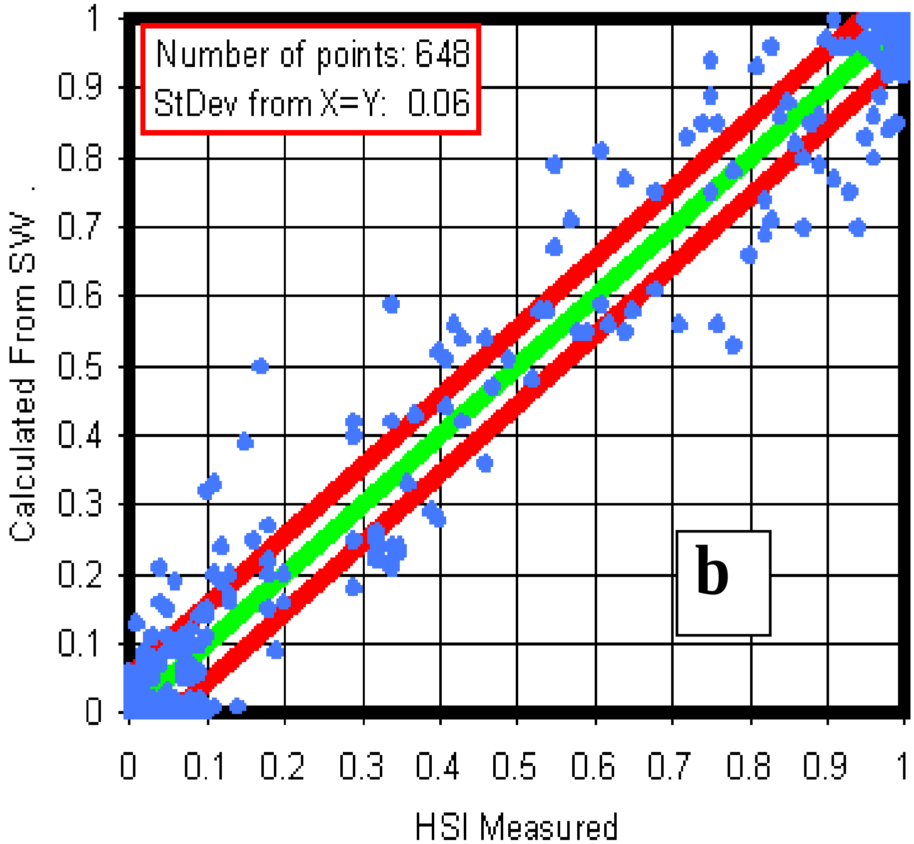
The clear-sky/cloud effect analysis has also resulted in the development of a novel quality control for surface solar radiation data. Specifically, information provided by the clear sky irradiance algorithm may be used to objectively determine when the solar tracker is properly aligned. This is accomplished by combining the measured and estimated clear-sky diffuse solar and global solar irradiance values in various ways. For example, comparing the ratio [measured global SW / clear-sky SW] to the ratio [measured diffuse SW / measured global SW] indicates whether the solar tracker is on target. These QC flags are in the .swf files, but not in the .c15 files.

Cloud fraction estimates from the clear-sky irradiance results

Because the TSIs are new to SURFRAD, a method has been developed to estimate hemispheric cloud fraction from the clear-sky analysis data (Long et al.,1999). Comparisons of these *estimated* cloud fractions to *HSI-derived* cloud fractions in Fig. 2 (from Long et al., 1999) show that the hemispheric cloud fraction may be estimated from solar irradiance data alone to within 10%. These plots were generated using carefully screened HSI data. Figure 3 shows a similar comparison, but using over 3 months of PSU SURFRAD TSI data. For the latter, neither the irradiance data nor the sky imager data were screened, but were used exactly as one would get them from the SRRB archive. The RMS disagreement for this operational data is about 14%. This serves to illustrate that the added uncertainty of unscreened operational sky imager retrievals increases the RMS difference over that of the tightly controlled data in Fig. 2. However, the RMS difference of 14% is still encouraging, given that observer estimates of sky cover are likely comparable. Thus, both the TSI and SW retrievals appear to be viable means of inferring sky cover. As such, we plan to investigate the possibility of using the comparison of both these data streams to assess the quality of the TSI data at each site.

The original regression relationship for inferring sky cover from normalized diffuse cloud effect data was derived using the prototype HSI. Unfortunately, the original camera used in the prototype, a Connectix Color QuickCam, failed due to exposure, and these cameras are no longer available from the manufacturer. Thus no direct comparison between sky cover retrievals from the Yankee TSI (which uses a proprietary modified camera based on the Axis WebCam), and the prototype HSI is possible. The comparison in Fig. 3 uses TSI sky cover retrievals and SW sky cover retrievals based on the original HSI-derived





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linear relationship. If there were significant differences between the TSI and original prototype HSI retrievals, then these differences would be evident in Fig. 3. The RMS difference of 14% is easily accounted for by increased operational uncertainties in the data.

Availability of the interpolated soundings at SURFRAD locations

In previous years of this contract, software was developed to interpolate soundings to SURFRAD station locations using NWS operational rawinsonde network data. Temperature, dew point temperature, geopotential height, and wind are interpolated. Input NWS soundings are first vertically normalized to common 25-mb pressure levels from 1000 to 100 mb, and then interpolated horizontally at those levels to the locations of the SURFRAD stations. Balloon drift is accounted for and special steps have been taken to stabilize the interpolations near the surface. The method used for the horizontal interpolation is the analytic approximation described in Caracena (1987).

In this past year, sounding interpolations were performed for all 0000 and 1200 UTC synoptic times for the duration of the SURFRAD network (1995 to the present). After all of the historical soundings were processed, a method was developed to automatically retrieve and process the national network sounding data within a day of real time. This ensures that interpolated soundings are available at about the same time that the station data are released for a particular day. To quality control the daily interpolated soundings, software was developed to compare the interpolated profiles to nearby NWS soundings. These comparisons are made each day as part of the daily SURFRAD interactive data quality control procedure. If problems are found, they are addressed and the sounding data are reprocessed.

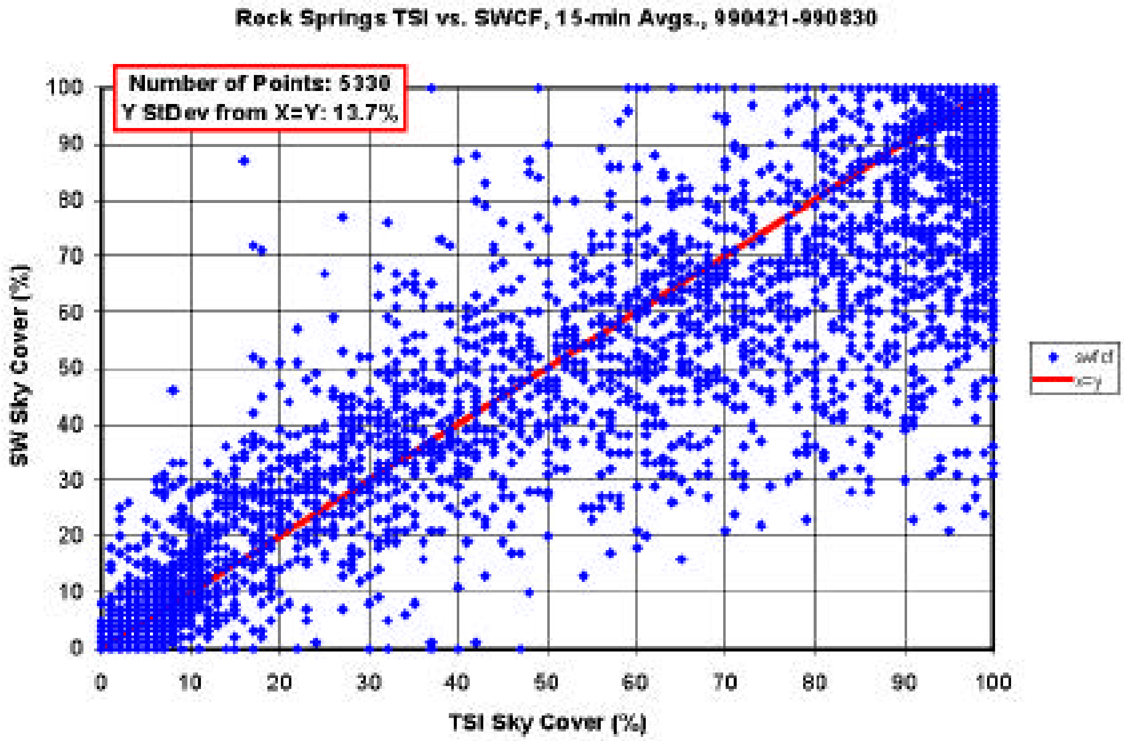

Fig. 3 Comparison of SW-estimated and TSI measured sky cover 15-minute averages for the Penn State University SURFRAD site, similar to Fig. 2. Red line represents X=Y.

Separate files for 0000 and 1200 UTC of each day from Jan. 1, 1995 to the present, are available from the "Soundings" link on the SURFRAD web page, i. e., <http://www.srrb.noaa.gov/surf/sndform.html>. Each of these files contains interpolated soundings for five SURFRAD stations and the actual sounding for Desert Rock. Any interpolated sounding may be downloaded or plotted on a skewT-logP background from the web page. A text file that explains the sounding file format is also available at the web site. For convenience, compact disks of the interpolated soundings are available upon request to EOS investigators.

Accuracy of the interpolated soundings assessed

During the past year, efforts were made to assess the accuracy of these interpolations using soundings from the ARM SGP Central Facility in Oklahoma. The ARM sounding is independent of the national network and thus is not used in the interpolation. Interpolated soundings for the location of the SGP Central Facility were compared to actual soundings taken there for all of 1998. All measured variables were compared. The temperature interpolation accuracy for all 0000 UTC soundings of March 1998 is summarized in Fig. 4. Most of the interpolated temperatures are within ±2°C (and nearly all are within ±4°C) of the measured values. The greater number of outliers at the uppermost levels reflect the larger uncertainties of the measurements at those levels, and to problems related to balloon drift. The monthly median values (the white lines inside the black boxes in Fig. 4) are mostly all within ±1°C of the measured monthly medians.

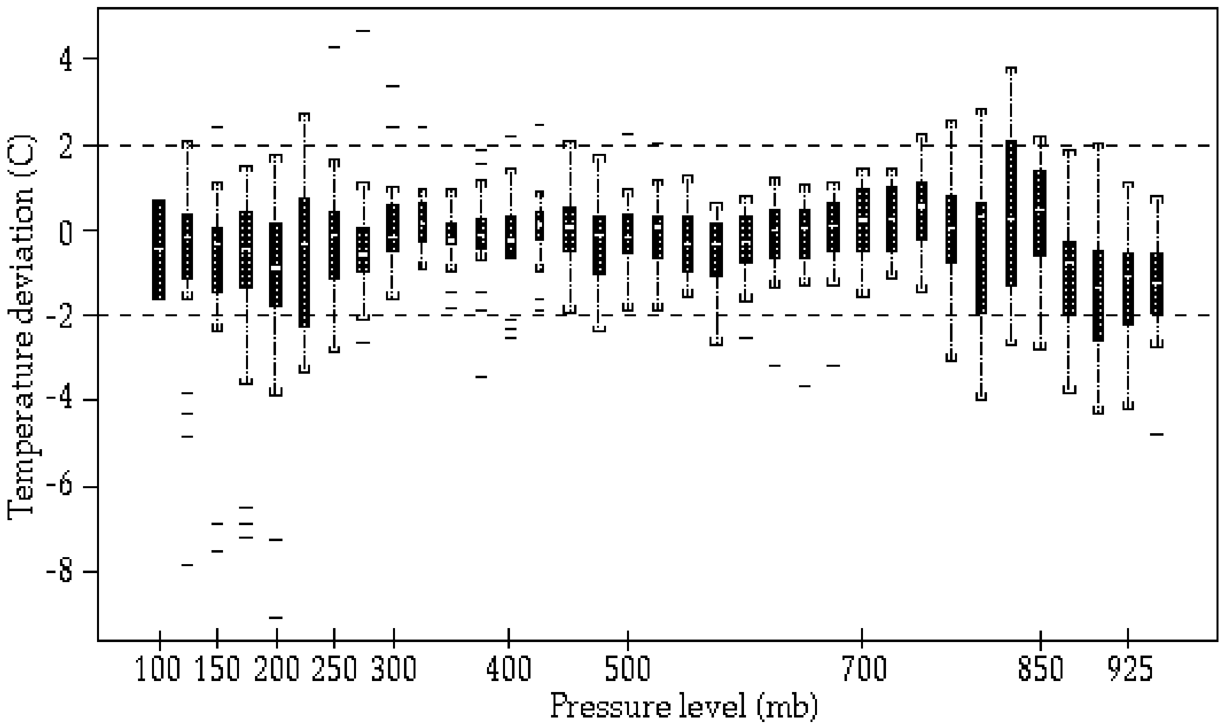

Fig. 4 Boxplots of temperature residuals for all 0000 UTC soundings of March 1998 between the interpolated and actual soundings at the ARM SGP Central Facility. All data except outliers are contained within the square brackets. The heavy black lines represent the middle 50% of the sample. Outlier data are represented by small horizontal lines.

However, this comparison is not optimal owing to several problems. First, the interpolated sounding at the ARM site is vertical (because balloon drift is accounted for in the interpolation process), but the actual ARM radiosonde drifts downwind as it rises. Thus, at upper levels, values being compared may represent locations that are 50 to100 km apart. Also, there are known errors in the operational soundings, such as histeresis in the dew point temperature above the boundary layer, which appears to be less severe in the interpolated soundings (see the 700-mb level Fig. 5). A better way to assess the value of the interpolated soundings would be to initialize a radiative transfer model with the interpolated soundings and compare the derived IR irradiance to the measured values at the stations. We hope to attempt this type of validation if we are funded for another year.

Measurement accuracy and precision assessed

Re-analysis code was developed to account for the drift of the instruments' calibration factors during their tenure at the stations. The successful application of this code to the entire SURFRAD data set was summarized in last year's report. This capability exists and may be applied to the data at any time, upon request. To add value to this product, the precision and accuracy of SURFRAD measurements were assessed.

Precision of the measurements was quantified using the pseudo overlap data from each year's instrument exchange. These data were compiled for all annual instrument exchanges that have taken place. The pyranometers were found to be quite stable; the mean absolute difference between the returning and replacement instruments was 1.2%, with a standard deviation of 0.9%. In contrast, the Quantum sensors (PARs) were found to be less

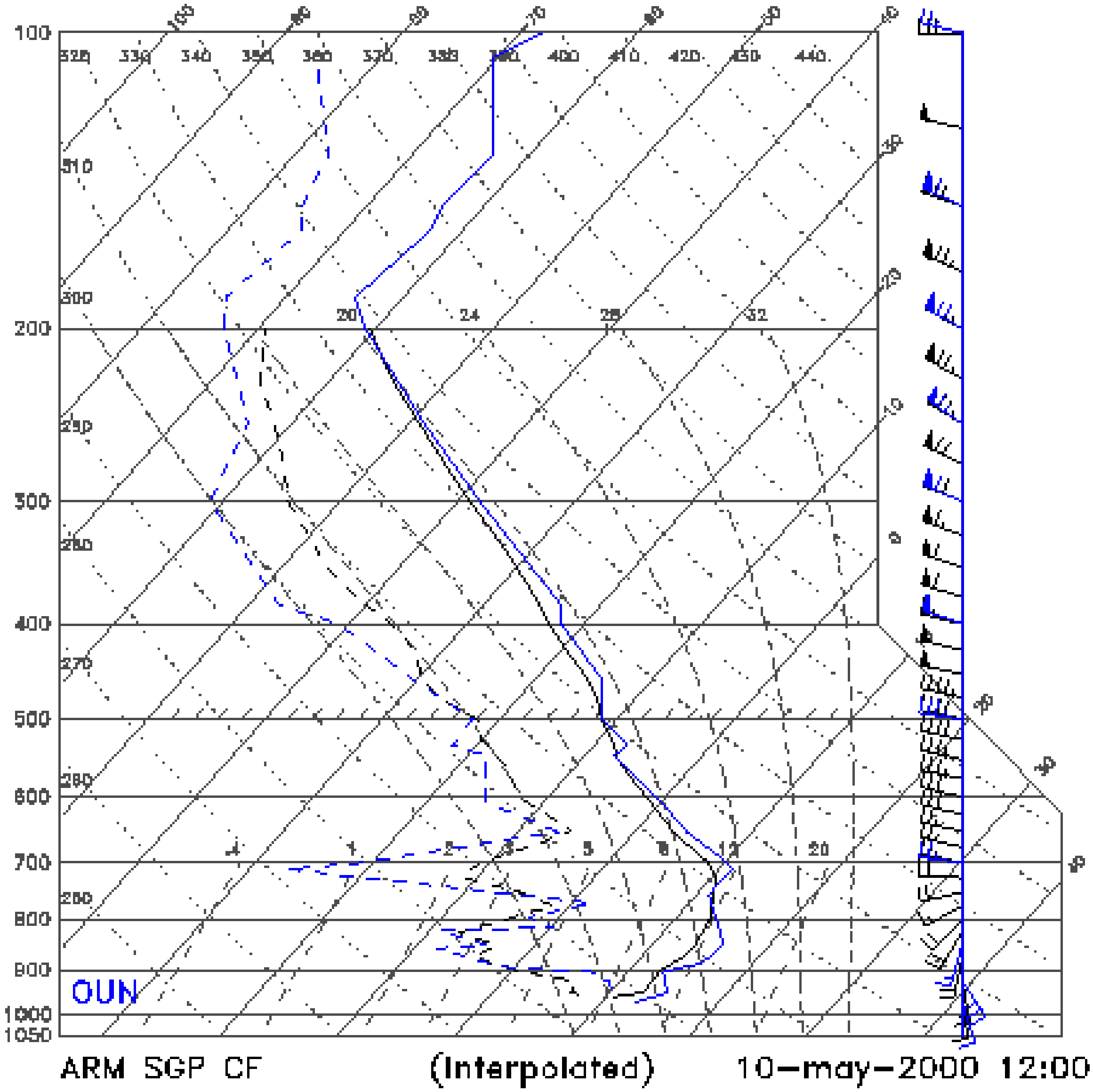

Fig. 5 Interpolated sounding for the ARM-SGP site (black) and the nearest actual sounding from at Norman, OK (OUN, blue) for May 10, 2000 at 1200 UTC. Temperature is plotted with solid lines and dew point temperature is plotted with dashed lines. Note the erroneous drying above the boundary layer at about 700 mb in the Norman sounding, and the less dramatic drying in the interpolated sounding.

stable, with a mean absolute difference of 4.7% and a standard deviation of 3.6%. The behavior of the latter was expected because the Quantum sensor is an inexpensive filtered instrument that is not thermally stabilized, as are the UVB radiometer and MFRSR. For the UVB instruments and pyrgeometers, the pseudo overlap information is used to calibrate those instruments, and thus can not be used to quantify their precision.

The accuracy of the SURFRAD measurements was also assessed. The reference pyrgeometers are calibrated at the World Radiation Centre (WRC) in Davos, Switzerland. The reported accuracy of their calibrations is ±4 Wm^{-2}. To transfer the calibrations of the reference pyrgeometers to the monitoring instruments, test and reference instruments are operated together for a week to ten days. Periods of stable signals common to both sets of instruments are objectively isolated for daytime and nighttime periods. Calibration equations, reported in Albrecht and Cox (1977), are written for each of those two periods using mean signals from the test instruments, and setting both equations equal to the mean irradiance from the reference instruments. The two equations are then solved for the constants in the calibration equation. This calibration transfer technique appears to improve the test instruments' absolute accuracy such that typically >99% of the test data are within ±5 Wm^{-2} of the reference set. Adding the reported uncertainty of the references' calibrations yields an uncertainty of ±9 Wm^{-2} for SURFRAD's monitoring pyrgeometers.

The method employed at the National Renewable Energy Laboratory (NREL) to calibrate SURFRAD pyranometers and pyrheliometers is the Broadband Outdoor Radiometer Calibration (BORCAL) (Reda, 1999). The BORCAL procedure uses the sun as the source. Direct and diffuse components of solar radiation are measured independently using an absolute cavity radiometer and a shaded pyranometer, respectively. The calibration of the cavity radiometer used at NREL is traceable to the World Radiation Reference (WRR) standard at the WRC. Cavity radiometer data are used to directly calibrate pyrheliometers, and the combination of the cavity data and diffuse measurements is used to calibrate the pyranometers. Only cloudless periods with small variations in the solar signal are used, thus minimizing the contribution of the diffuse component, which has the highest uncertainty. Although measurements are taken throughout the day, only those made between 45° and 55° solar zenith angles are used to fix the sensitivity factors, because the cosine errors of pyranometers are typically near zero in that range. Average uncertainties from the BORCAL procedure generally range from ±2% to ±5% for pyranometers and ±2% to ±3% for pyrheliometers.

The UVB reference instruments are used to calibrate the network UVB instruments. A test instrument is run alongside the three references for at least a week. A scale factor, defined as the ratio of the test instrument's daily integral of UVB irradiance to the mean daily integrated irradiance of the three references, is computed for each day that the instruments are operated together. The representative scale factor that transfers the references' mean calibration to the field instrument is the average of the daily scale factors. The variation in the daily scale factors is usually less than ±1%. Adding to this the reported ±4% error of the UVB standards (Lantz, et al., 1999) yields ±5% for the monitoring UVB instruments.

Accuracies of all SURFRAD instruments are summarized in Table 3. The uncertainties presented should be considered ideal because "operational uncertainties," which are difficult to quantify, are not included. These include calibration drift, differences between operating in cold versus warm ambient temperatures, cosine effects, etc. However, Table 3 is an indication that we are going about this in a quite reasonable manner given the difficulties in long-term measurement programs. A history of instrument suites deployed at SURFRAD stations and their associated calibration values for all monitoring epochs are available from the "Calibrations" link of the SURFRAD section of the SRRB web site <http://www.srrb.noaa.gov>.

Improvements at SURFRAD stations that benefit EOS validation

Always striving to better the quality of SURFRAD products, several improvements have been made at the stations, and others are planned. Historically, the primary source of missing data was the antiquated solar trackers that were originally used at the stations. Near the end of FY 1999 NOAA funded the purchase of modern solar trackers for SURFRAD at a cost of $82K. At this point, all but two have been installed. This has greatly increased the good-data collection efficiency. Another improvement is the transfer of the downwelling

Table 3 Data quality of SURFRAD monitoring instruments

Instrument	Manufacturer	Model	Measurements	Accuracy
Pyranometer	Spectrolab and Eppley	SR-75 (Spectrolab) PSP (Eppley)	global, diffuse, upwelling solar irradiance	±2% to ±5%
Pyrgeometer	Eppley	PIR	downwelling and upwelling infrared irradiance	±9 Wm^{-2}
Pyrheliometer	Eppley	NIP	direct solar irradiance	±2% to ±3%
UVB Radiometer	Yankee Environmental Systems	UVB-1	global ultraviolet B erythemal irradiance	±5%
Quantum Sensor	LI-COR	Quantum	global photosynthetically active irradiance	±5%
Temperature and Relative Humidity Probe	Vaisala	CS500	air temperature relative humidity	±0.5°C ±2-3% below 90% RH, and ±6% above 90% RH
Wind Monitor	R. M. Young	05103	wind speed and direction	± 2% for wind speed ± 5° for wind direction
Barometer	Vaisala	PTB101B	station pressure	±4 mb (-20° to 0°C) ±2 mb (0° to 40°C)

PIR from the main platform to the solar tracker, which is being carried out at the instrument exchanges during 2000. This is in compliance of the BSRN recommendation that PIRs should be operated in a shaded mode.

Last, it has been known for some time that single detector thermopile pyranometers commonly used for solar monitoring have an erroneous nighttime offset owing to infrared effects of the inner dome. Furthermore, its impact on the daytime measurements is not clear. The diffuse measurement is affected most severely. Using results presented at the 2000 ARM science Team meeting's "Diffuse Irradiance Breakout Session," and at the 2000 BSRN meeting, it has been decided to use the Eppley model 8-48 pyranometer for the diffuse measurement in SURFRAD as at least an interim measure to help alleviate the IR loss problem. Because of the way the Eppley 8-48 sensor is designed (alternating black and white surfaces with the signal registered as the differential between the two surfaces), there is no nighttime, or daytime, offset. This will improve the accuracy of the diffuse solar measurements. In fact, considering accuracy, maintenance, and reliability, the results presented at these two meetings suggest that for the current level of technology, this might be the most cost-effective solution for SURFRAD. New model 8-48 pyranometers have been purchased and will be deployed next year.

Beginning with the first BORCAL of 2000, NREL will be using the model 8-48 for measuring the diffuse component in their calibration procedure for pyranometers. Results of the first BORCAL were reported on May 16 and show that the new procedure reduces pyranometer sensitivities by about 3%. Since sensitivity factors are applied as divisors, this implies that all past global and diffuse solar measurements made with NREL-calibrated single detector pyranometers are, on average, 3% low.

Collaborations with the CERES Science Team

We attended the CERES Science Team meetings in April of 1998 and 1999, and made arrangements to supply soundings and other CERES-specific SURFRAD data to Tim Alberta for the January 1998 period when TRMM CERES instrument was activated. We were recently contacted by Ann Nolin of The University of Colorado, an EOS validation scientist, concerning the use of the Fort Peck SURFRAD site as ground truth for MODIS estimates of albedo, spectral albedo, and other properties of snow surfaces. This work will be done over a two-three week period in conjunction with JPL. At the SURFRAD station, they will time their special surface measurements with a simultaneous EOS satellite overpass and a NASA research aircraft fly-over.

Publications

An article describing the SURFRAD network (Augustine et al., 2000) entitled "SURFRAD—A national surface radiation budget network for atmospheric research," which discusses the NASA-EOS/SURFRAD collaboration, has been accepted by the *Bulletin of the American Meteorological Society* will appear in the September issue. Another article on the clear-sky identification/cloud effects algorithm entitled "Identification of Clear Skies from Broadband Pyranometer Measurements and Calculation of Downwelling Shortwave Cloud Effects," has been accepted by the *Journal of Geophysical Research* (Long and Ackerman, 2000) and will be published in either the July or August 2000 issue. Last, a paper entitled "Estimation of Fractional Sky Cover from Broadband SW Radiometer Measurements" (Long et at., 1999) was presented at the 10th Conference on Atmospheric Radiation, June 28-July 2, 1999, Madison, Wisconsin. Copies of these papers are available on request.

Planned activities

Activities for the coming year span a broad list of items to wrap up this investigation. Much of the TSI-related efforts will concentrate on the purchase and installation of hardware for disseminating the high resolution TSI data to EOS investigators, and on addressing solutions to design problems that need to be retrofitted to the SURFRAD TSI systems.

Since the clear-sky identification method has been validated, its application to SURFRAD data will be converted from experimental to operational mode. Results will be available to EOS investigators on a monthly time frame.

The exercise carried out to validate the interpolated soundings at SURFRAD stations was not optimal. To supplement these results, an exercise will be carried out to radiatively validate the interpolated soundings. The interpolated soundings will be used to initiate the University of Maryland radiative transfer model to compute the downwelling infrared irradiance. Actual measurements at SURFRAD stations will be used to validate the model results.

Last, because past efforts were unsuccessful, new methods will be developed to extract aerosol optical depth information from SURFRAD MFRSR data using the clear-sky ID results.

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